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Technical Report

DYNAMIC TESTS ON SELECTED STRUCTURAL STEELS

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DYNAMIC TESTS ON SELECTED STRUCTURAL STEELS

Technical Report R-642

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by

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ABSTRACT

Dynamic tension tests and static tension tests were conducted on four grades of structural steels. The steels conform to ASTM grades A36, A242, A441, and A572. Stress–strain curves are presented for each steel at various strain rates, ranging from static to about 1.5 in./in./sec. While all steels showed an increase in yield stress with increasing strain rates, the A36 steel showed the greatest increase. Design recommendations are given for structural steels subjected to high strain rates.

Additional specimens were strain aged, and stress–strain curves were obtained for both dynamic and static tests. Of the strain-aged steels, only the A36 steel showed a significant increase in strength over the non-strain-aged steels, when loaded dynamically. No adverse effects of strain aging were noted on any of the steels.

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INTRODUCTION

This report deals with one of several studies conducted by NCEL to determine the dynamic properties of basic structural materials. The objective of the studies is to obtain fundamental information applicable to the design of structures capable of resisting blast or other dynamic loads. Steel structures may undergo strain aging when subjected to multiple blast loadings. Therefore, dynamic tests were conducted on various grades of structural steel to explore their strain rate sensitivity and the effects of strain aging on stress–strain relationships.

STEELS TESTED

Four grades of steel were selected for testing. Three grades conformed to the American Society of Testing Materials (ASTM) Designations A36, A242, and A441. One steel, Ex-Ten 50, was selected to represent a relatively new group of steels referred to as columbium-vanadium steels, designated by ASTM as A572.

Each grade of steel was obtained in 1/4-inch-thick hot-rolled plate. In addition, a sample of the A242 steel was obtained in 7/8-inch-thick hot-rolled plate. The chemical content of each steel, as shown by the mill analysis supplied by the manufacturer, is shown in Table 1.

Table 1. Chemical Analysis of Structural Steels

Steel Grade*	Chemical Constituents (% by weight)								
	C	Mn	P	S	Si	Cu	Ni	Cr	V
A36	0.22	0.41	0.008	0.020	–	–	–	–	–
A441	0.18	0.78	0.012	0.026	0.10	0.40	–	–	0.06
Ex-Ten 50	0.20	1.23	0.016	0.022	0.04	–	–	–	0.06
A242	0.09	0.37	0.088	0.021	0.36	0.38	0.35	0.94	–
A242 (7/8-in.-thick plate)	0.09	0.42	0.120	0.030	0.56	0.39	0.40	0.98	–

* All specimens 1/4-in. thick except where noted.

TEST SPECIMENS AND INSTRUMENTATION

Test specimens fabricated from the 1/4-inch hot-rolled plate were machined according to the dimensions given in Figure 1. The specimens fabricated from the 7/8-inch hot-rolled plate were machined according to the dimensions given in Figure 2.

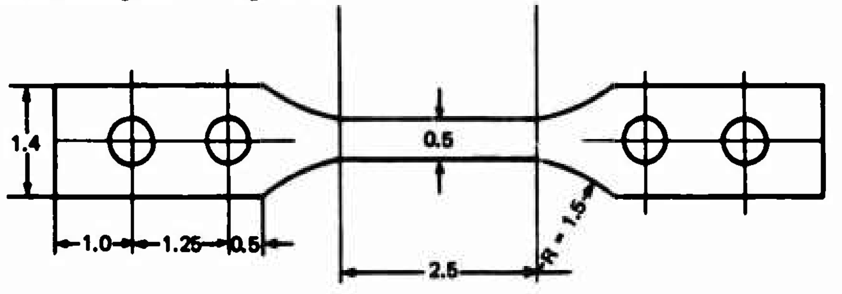

Figure 1. Flat test specimen.

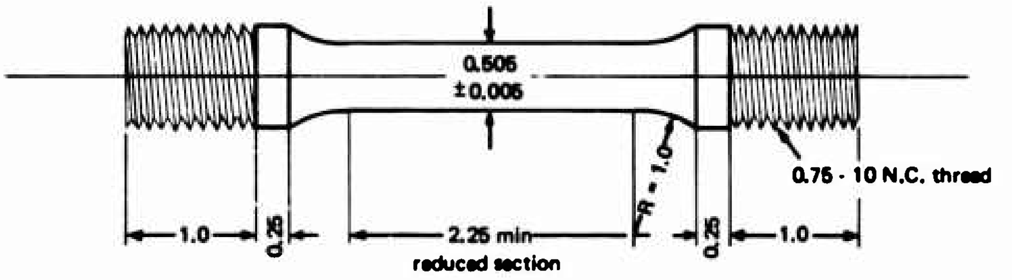

Figure 2. Round test specimen.

Elastic strain in the reduced section of each specimen was measured with a 1/2-inch-gage-length foil-type resistance strain gage connected to one leg of a Wheatstone bridge. The remaining three legs of the bridge were formed with similar gages cemented to a small block of steel. Load was measured with a tension link composed of resistance strain gages; the link was calibrated on a standard universal testing machine.

Plastic strain was measured with a transducer unit consisting of a light-photocell-grid-tape arrangement, as shown in Figure 3. The spring-loaded clamps (with knife edges) were attached to the specimen utilizing a 2-inch gage length. The transducer unit was secured to the upper set of clamps, as shown. A plastic tape consisting of alternate transparent and opaque sectors of equal width was secured to the lower set of clamps, and the other end was passed through a slot in the transducer unit. As the specimen is strained, the tape is drawn through the slot. Light passing through the gate is alternately blocked or allowed to pass through the

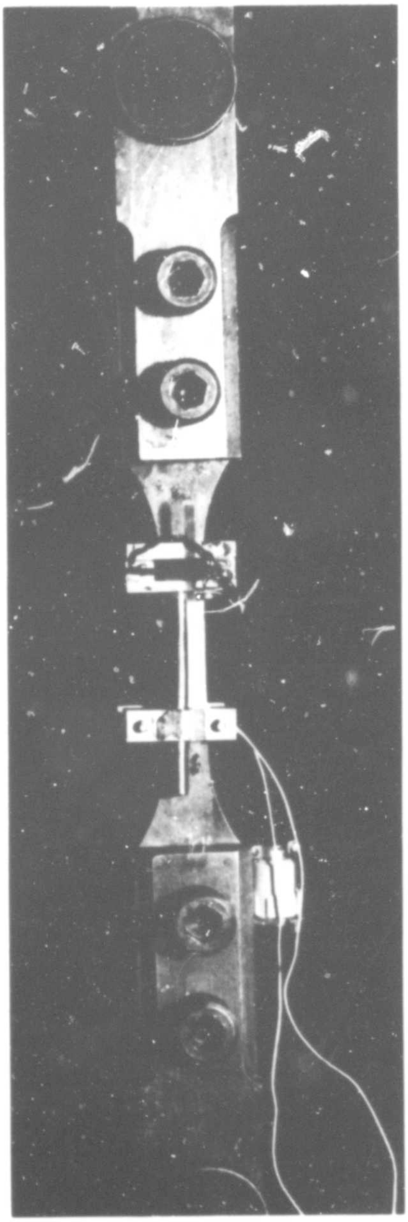

Figure 3. Assembled flat test specimen, illustrating transducer unit for measuring large strains.

opaque or transparent sectors on the tape and to impinge upon the photocell. The output from the photocell is recorded as a sine wave and represents a known displacement of the clamps. A representative test record is shown in Figure 4.

Test data were recorded on an oscillograph by means of system D, 3-kHz amplifiers. When the strain rate exceeded 1.0 in./in./sec, test data were recorded by means of a dual beam oscilloscope and a Polaroid camera.

TESTING MACHINES

All dynamic tests were conducted on a high-speed pneumatic-hydraulic testing machine. This machine is shown in Figure 5, and a full description of it may be found in Reference 1.

The initial straining of test specimens to determine the effects of strain aging on the dynamic properties of steels was conducted on a Tinus-Olsen universal testing machine.

TEST PROGRAM

Complete static stress–strain curves were determined for each steel. The testing rate was maintained at 10^{-5} in./in./sec through the plastic range and then increased to approximately 8×10^{-4} in./in./sec for the remainder of the test.

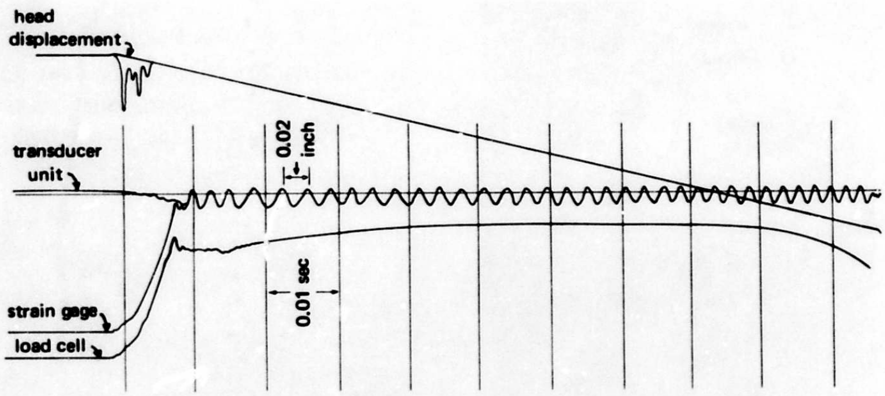

Figure 4. Typical oscillograph record of stress time and strain time for dynamic loading.

Dynamic tests were conducted on each steel at various strain rates in the elastic range up to a maximum rate of 1.54 in./in./sec at room temperature. This enabled the construction of curves showing the variation in mechanical properties as a function of the strain rate.

To obtain the effect of strain aging on the mechanical properties of the materials each steel specimen was prestrained to 4% strain and the load was released. The specimens were then placed in oil at 60°C for 72 hours to accelerate aging. After being allowed to cool, the specimens were tested dynamically at one of the strain rates previously used in the regular dynamic tests. Tests were conducted to determine the length of time necessary to obtain maximum strain-aging characteristics for each steel.

TEST RESULTS

Test results are shown in Tables 2 through 6. The elastic strain rate was calculated from the trace of the oscillograph record of the strain gage located in the reduced section of the specimen. The plastic strain rate was calculated from the trace of the oscillograph record of the transducer unit described earlier and represents an average strain rate in the strain-hardening region of the stress—strain curve. The load, from which the stresses are derived, was calculated from the strain reading of a tension link. Stress—strain curves for each strain rate used are given in Figures 6 through 10. Each curve is generally the average of three specimens.

The results of tests to determine the effects of strain-aging on the mechanical properties of steels subjected to dynamic loading are shown in Figures 11 through 14. Again, each curve is generally the average of three specimens. As noted earlier, the dynamic tests on strain-aged specimens were conducted at the same strain rates used in a regular set of dynamic tests, that is, 0.5 in./in./sec. The comparable dynamic tests on non-aged specimens are also illustrated for comparison.

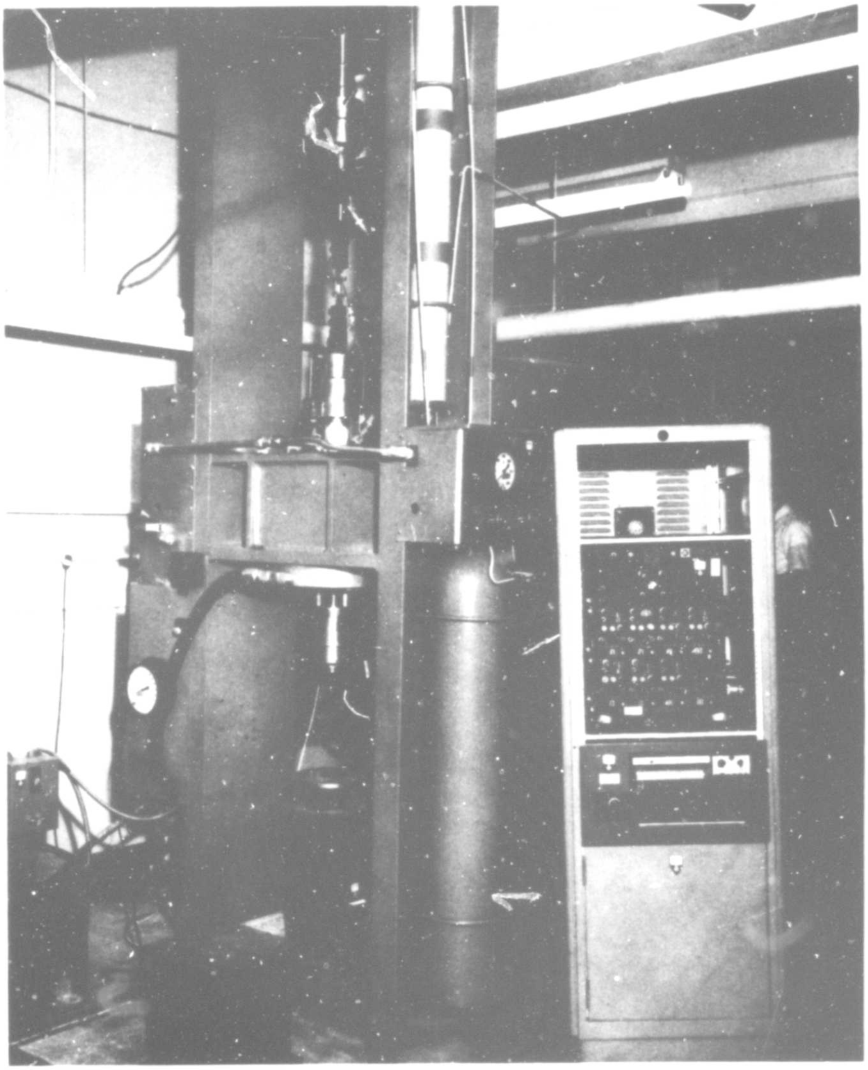

Figure 5. Dynamic testing machine.

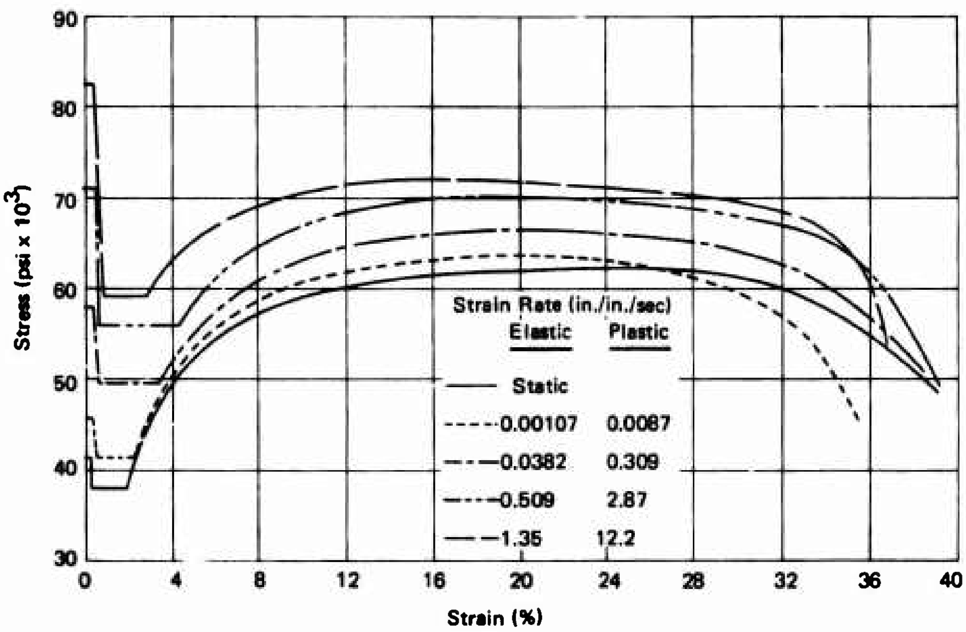

Figure 6. Effect of strain rate on the stress–strain curve of flat specimens of A36 steel.

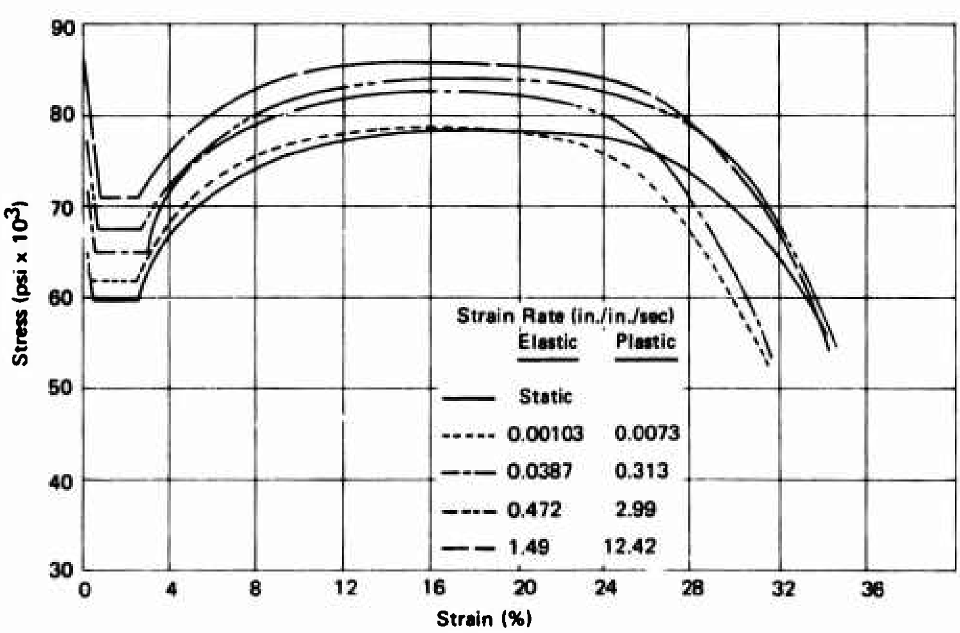

Figure 7. Effect of strain rate on the stress–strain curve of flat specimens of A242 steel.

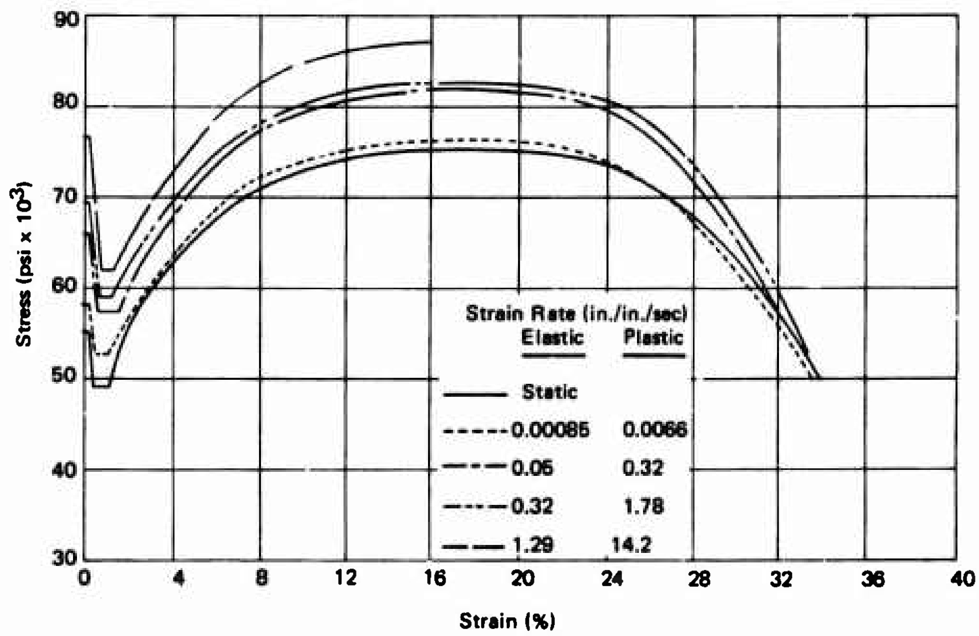

Figure 8. Effect of strain rate on the stress–strain curve of round specimens of A242 steel.

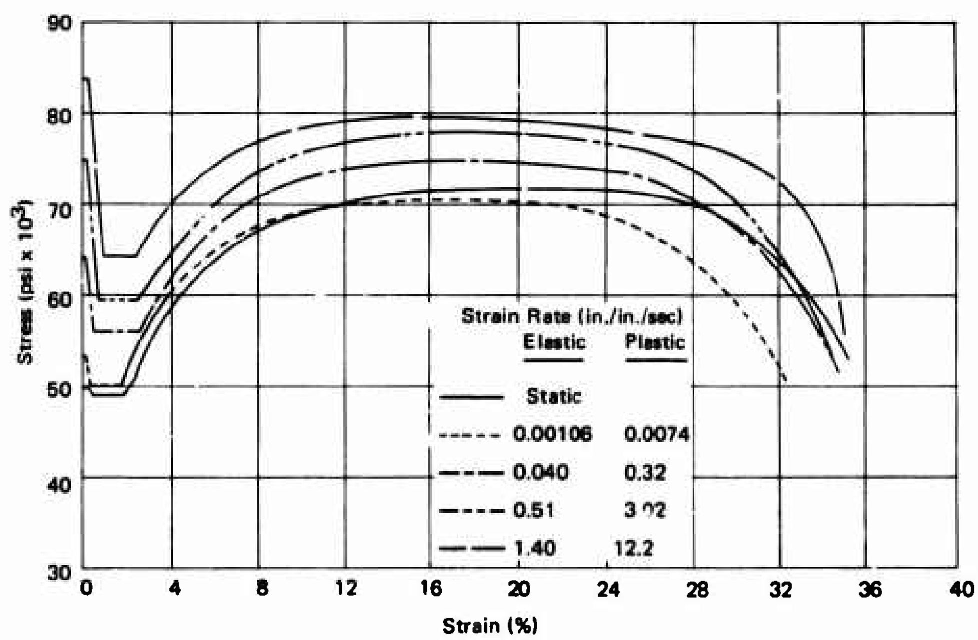

Figure 9. Effect of strain rate on the stress–strain curve of flat specimens of A441 steel.

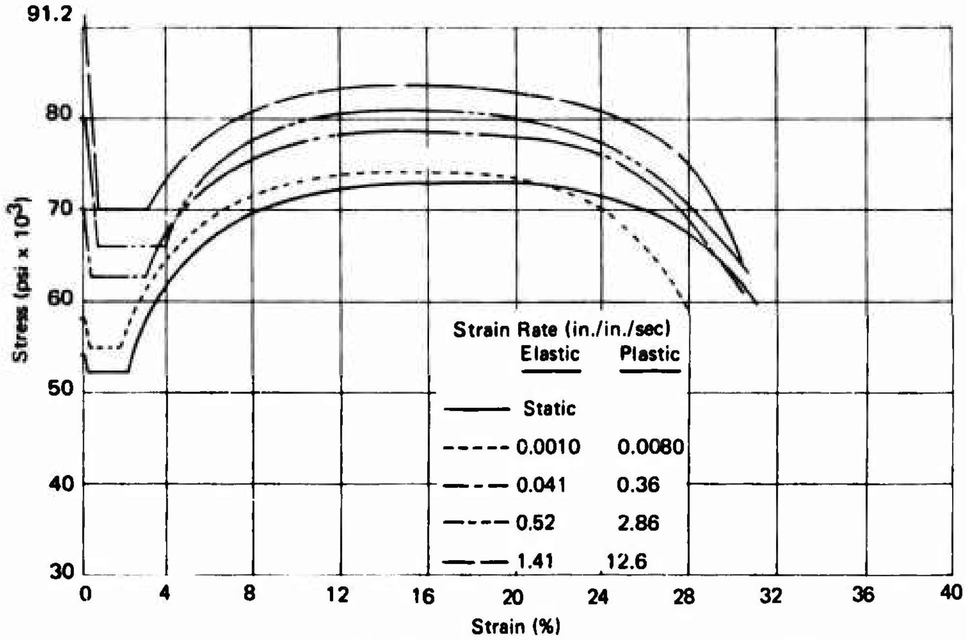

Figure 10. Effect of strain rate on the stress–strain curve of flat specimens of Ex-Ten 50 steel.

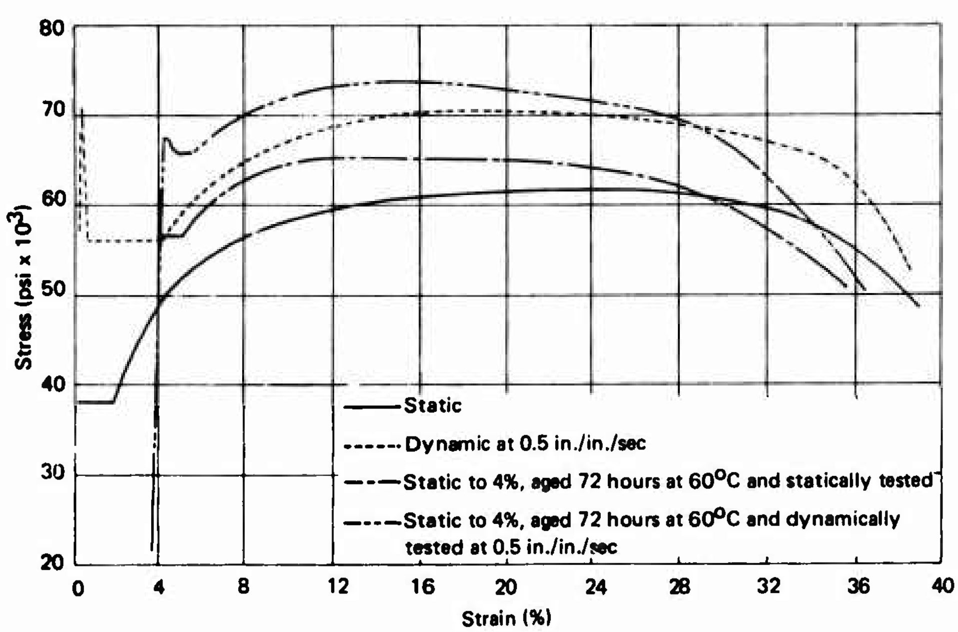

Figure 11. Effect of strain aging on the static and dynamic stress–strain curves of flat specimens of A36 steel.

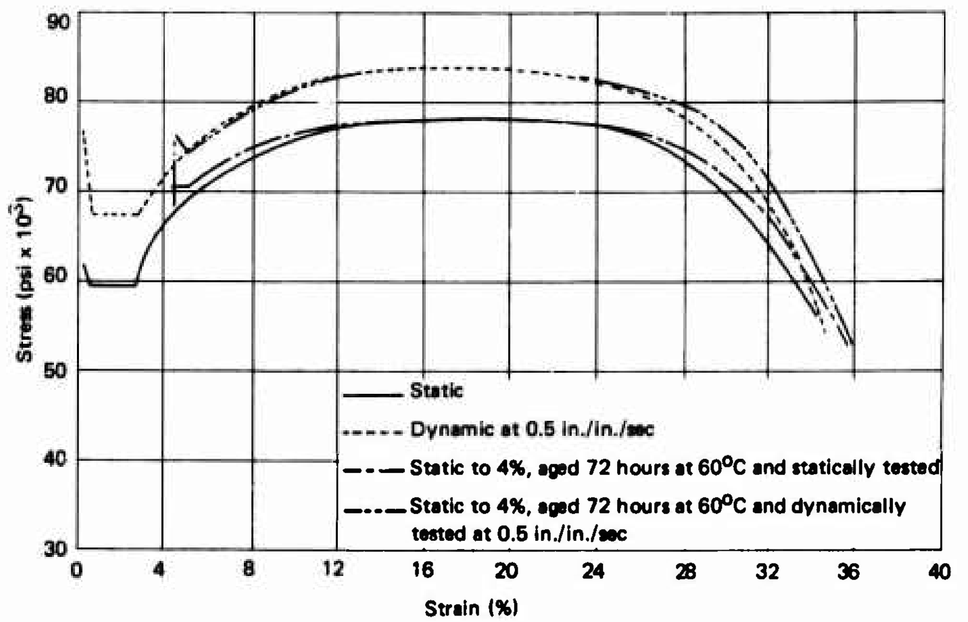

Figure 12. Effect of strain aging on the static and dynamic stress—strain curves of flat specimens of A242 steel.

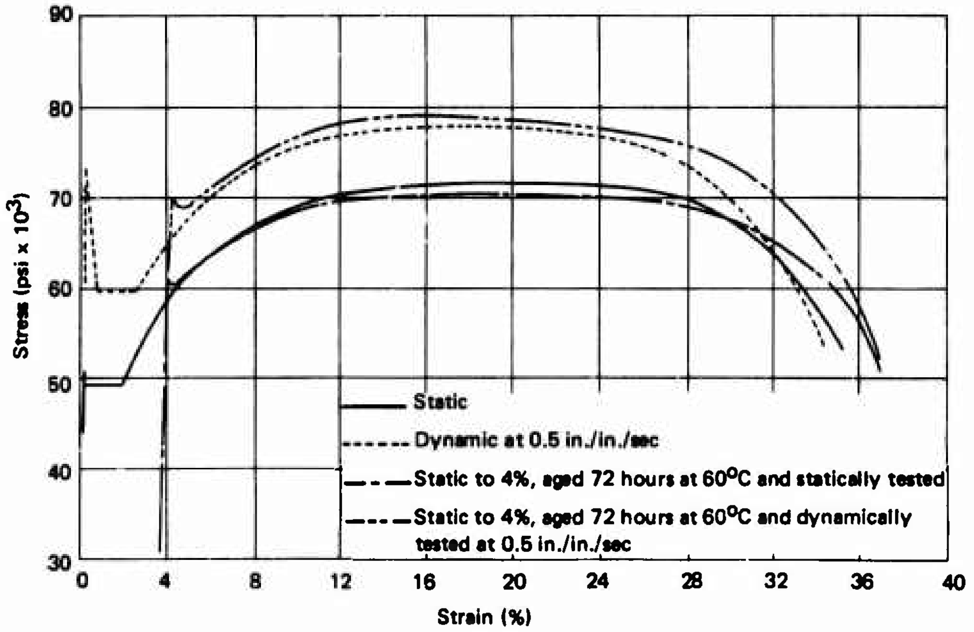

Figure 13. Effect of strain aging on the static and dynamic stress—strain curves of flat specimens of A441 steel.

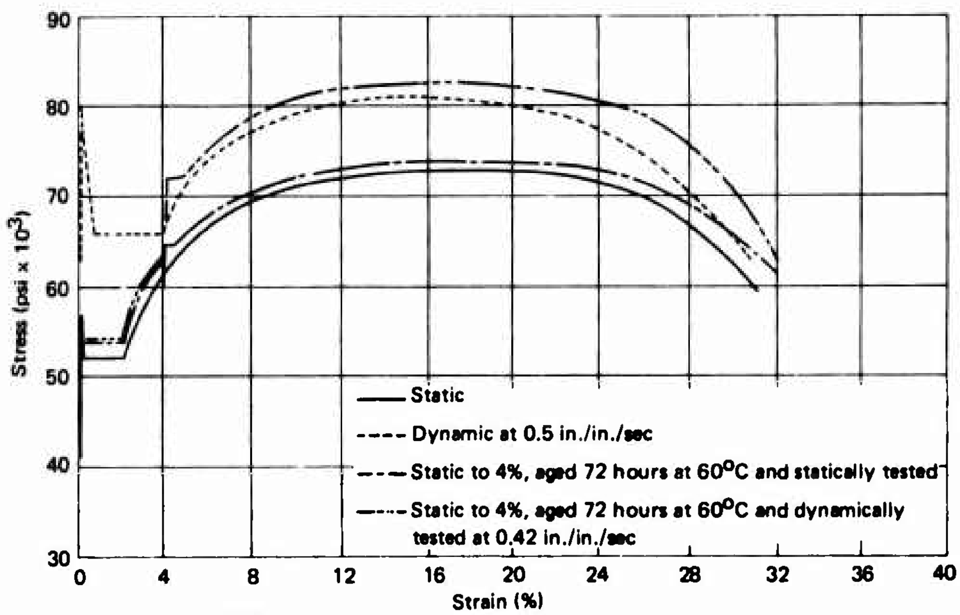

Figure 14. Effect of strain aging on the static and dynamic stress–strain curves of flat specimens of Ex-Ten 50 steel.

Because of its greater sensitivity to strain aging, more extensive aging tests both at room temperature and at 60°C were conducted on the A36 steel. Results of the tests on A36 steel are shown in Figures 15 and 16. Each curve represents one specimen.

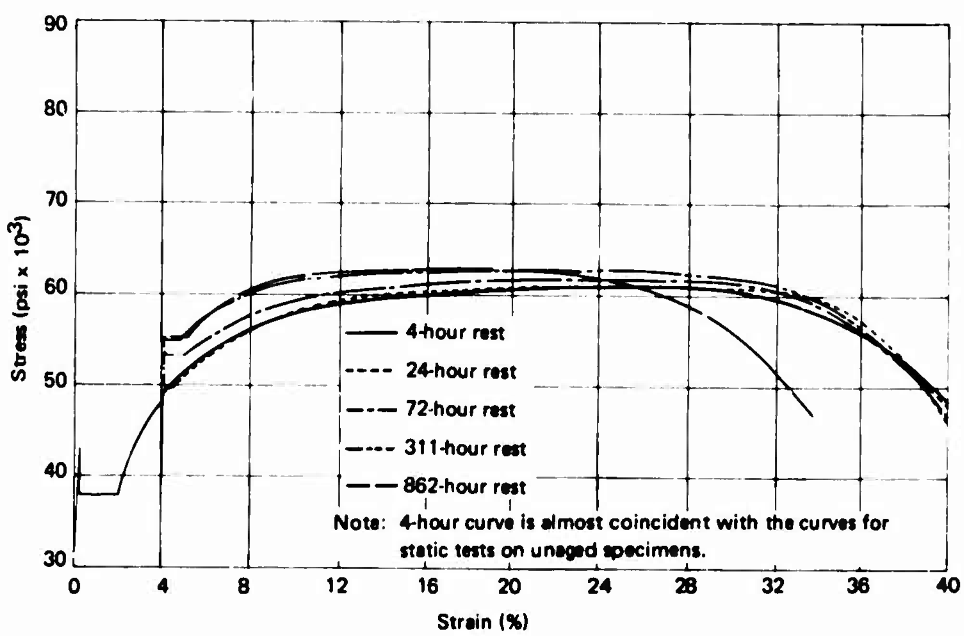

Figure 15. Effect of aging time at room temperature on strain aging characteristics of flat specimens of A36 steel.

Table 2. Results of Tension Tests on Flat Specimens of A36 Steel

Elastic Strain Rate (in./in./sec)	Plastic Strain Rate (in./in./sec)	Lower Yield Stress (psi)	Upper Yield Stress (psi)	Tensile Strength (psi)	Rupture Stress (psi)	Elongation (%)
Static (avg of 6 specimens)		38,000	41,400	62,200	48,600	40
0.00100	0.0080	41,100	44,800	63,100	46,400	36
0.00106	0.0095	41,300	46,700	63,000	46,200	37
0.00114	0.0087	42,500	46,900	63,600	45,700	36
0.0360	0.300	47,100	55,200	65,000	54,000	38
0.0362	0.308	50,000	60,500	67,500	47,800	40
0.0424	0.320	49,500	58,500	66,300	–	39
0.480	[illegible]02	56,000	69,900	69,100	49,100	39
0.516	2.66	54,000	71,500	69,500	48,400	39
0.530	2.92	58,000	72.100	71,100	50,100	41
1.23	13.5	60,400	82,900	72,500	48,700	45
1.37	13.0	57,700	82,400	71,500	48,800	39
1.44	10.0	59,500	82,700	72,000	50,700	40

Table 3. Results of Tension Tests on Flat Specimens of A441 Steel

Elastic Strain Rate (in./in./sec)	Plastic Strain Rate (in./in./sec)	Lower Yield Stress (psi)	Upper Yield Stress (psi)	Tensile Strength (psi)	Ruoture Stress (psi)	Elongation (%)
Static (avg of 3 specimens)		49,000	51,000	71,800	52,900	35
0.00089	0.00555	49,900	53,400	70,200	50,900	33
0.00107	0.0085	50,300	52,300	70,600	50,300	33
0.00122	0.0081	50,100	53,900	70,600	50,100	33
0.0389	0.308	57,900	63,300	75,700	51,500	38
0.0396	0.308	55,000	64,300	74,800	51,700	34
0.0416	0.333	54,900	64,600	74,300	51,900	35
0.424	3.09	60,600	73,100	77,600	53,000	36
0.500	3.08	58,600	77,500	78,300	53,400	35
0.600	2.88	59,100	75,000	77,8[illegible]	53,900	34
1.37	12.5	66,300	85,200	80,700	60,300	37
1.40	12.0	64,400	83,400	79,000	50,300	39
1.42	12.0	62,200	83,200	78,800	56,000	38

Table 4. Results of Tension Tests on Flat Specimens of Ex-Ten 50 Steel

Elastic Strain Rate (in./in./sec)	Plastic Strain Rate (in./in./sec)	Lower Yield Stress (psi)	Upper Yield Stress (psi)	Tensile Strength (psi)	Rupture Stress (psi)	Elongation (%)
Static (avg of 3 specimens)		53,000	56,000	73,300	59,500	32
0.00092	0.0091	55,100	55,100	75,000	65,600	28
0.00103	0.0091	54,200	58,700	72,900	58,300	28
0.00107	0.0064	55,800	60,800	74,700	59,600	29
0.0398	0.334	62,600	69,600	78,100	61,200	30
0.0405	–	63,200	71,400	79,800	61,200	34
0.0440	0.390	62,200	68,900	78,000	61,200	30
0.496	2.88	65,800	79,700	81,300	62,100	35
0.500	2.90	65,900	78,000	81,000	62,700	34
0.571	2.81	65,600	81,900	80,600	64,800	30
1.35	12.5	70,500	90,200	84,200	64,100	32
1.36	13.0	69,100	90,500	83,500	64,500	33
1.51	12.2	69,900	92,800	83,200	64,000	31

Table 5. Results of Tension Tests on Flat Specimens of A242 Steel

Elastic Strain Rate (in./in./sec)	Plastic Strain Rate (in./in./sec)	Lower Yield Stress (psi)	Upper Yield Stress (psi)	Tensile Strength (psi)	Rupture Stress (psi)	Elongation (%)
Static (avg of 5 specimens)		59,600	62,400	78,000	55,900	34
0.00078	0.0049	62,200	65,000	77,700	52,200	32
0.00101	0.0080	62,500	66,600	80,000	53,600	32
0.00126	0.0091	60,600	64,400	78,500	52,000	32
0.0362	0.308	63,400	70,200	81,100	52,300	36
0.0368	0.300	66,500	74,200	84,100	55,100	32
0.0430	0.330	65,100	72,800	80,900	52,800	33
0.450	3.16	67,800	76,900	83,800	54,700	36
0.480	2.92	67,100	76,000	84,100	54,300	34
0.485	2.88	68,000	77,900	84,200	54,500	36
1.41	12.0	71,200	84,500	85,800	53,100	37
1.51	12.25	70,000	85,400	86,200	55,500	35
1.54	13.0	71,800	88,100	85,500	53,900	34

Table 6. Results of Tension Tests on Round Specimens of A242 Steel

Elastic Strain Rate (in./in./sec)	Plastic Strain Rate (in./in./sec)	Lower Yield Stress (psi)	Upper Yield Stress (psi)	Tensile Strength (psi)	Rupture Stress (psi)	Elongation (%)
Static (avg of 3 specimens)		49,100	55,100	75,100	49,500	35
0.00082	0.00684	52,600	59,700	76,400	49,700	36
0.00089	0.00626	52,300	58,000	76,100	50,400	34
0.0465	0.321	57,000	65,100	81,200	51,900	33
0.0504	0.333	56,000	65,000	79,800	49,800	34
0.0522	0.320	58,900	67,400	84,400	55,800	33
0.241	1.55	58,400	67,600	81,600	51,400	35
0.303	1.50	57,800	68,900	81,800	51,500	34
0.426	2.30	60,200	71,800	84,600	54,500	33
1.20	13.5	60,000	76,300	83,800	52,500	–
1.32	14.0	63,300	77,100	88,400	54,000	36
1.36	15.25	62,300	76,400	86,000	53,000	37

OBSERVATIONS

Dynamic Test Series

The mechanical properties of all of the steels tested showed a general increase with increasing strain rates. Figures 17, 18, and 19 show the increase in upper yield, lower yield, and tensile strength, respectively, as a function of the strain rate (data from Tables 2 through 6). The findings of other investigators have been included in Figure 18 and will be discussed later. Figures 20, 21, and 22 depict the same properties in terms of a percentage increase over static values as a function of the strain rate.

In general, the A36 steel appears to be the most strain-rate sensitive of all the steels tested, particularly if compared on a percentage basis. The next most strain-rate-sensitive steel was the Ex-Ten 50, followed closely by the A441 steel. The A242 steel was the least strain-rate sensitive of the group, with the exception of the increase in tensile strength exhibited by the 7/8-inch specimens. This increase amounting to 10,900 psi at the maximum test rate, was the highest of all the steels (see Tables 2 through 6). When all the steel specimens are taken into account, the tensile strengths at the maximum strain rates ranged from 7,000 to 10,900 psi over static values, and this is similar to that found in tests conducted on reinforcing steels.[4]

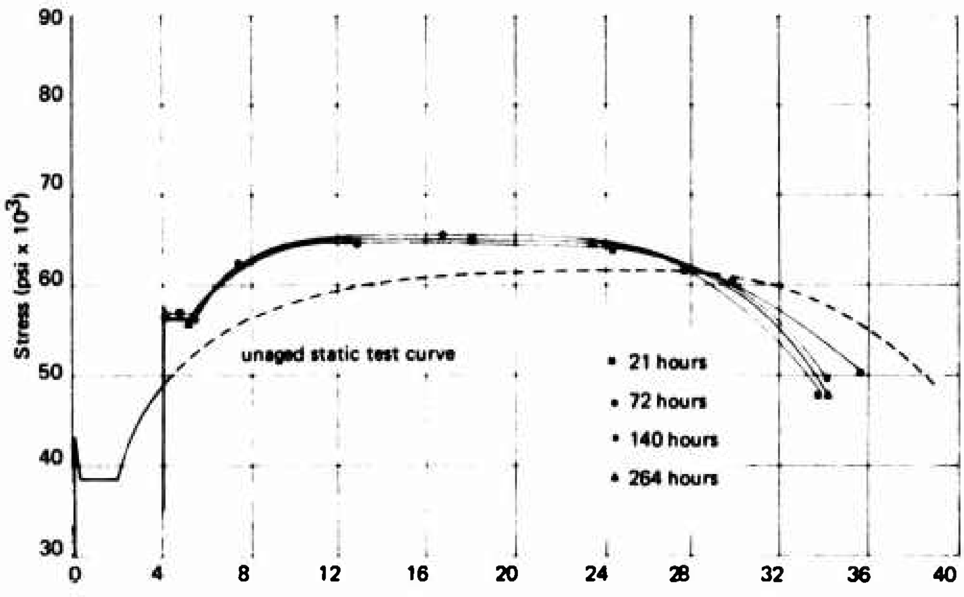

Figure 16. Effect of aging time at 60^oC on strain aging characteristics of flat specimens of A36 steel.

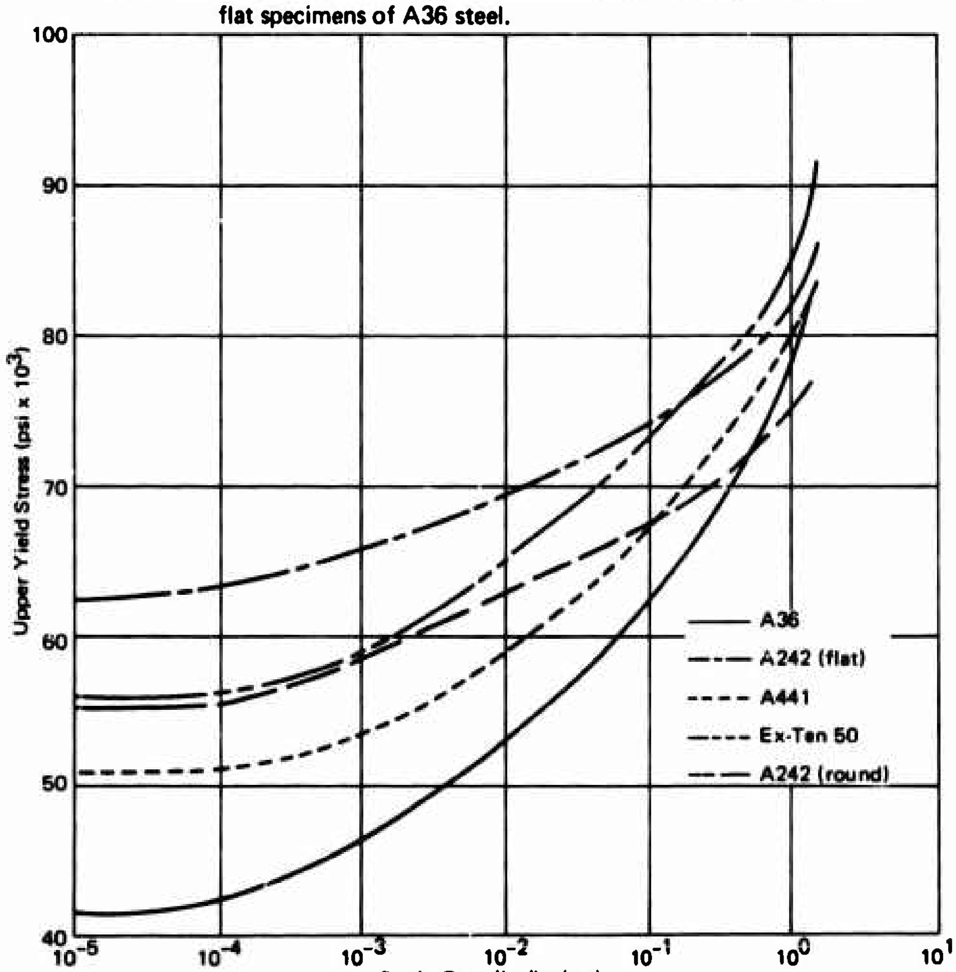

Figure 17. Upper yield stress versus strain rate for structural steels.

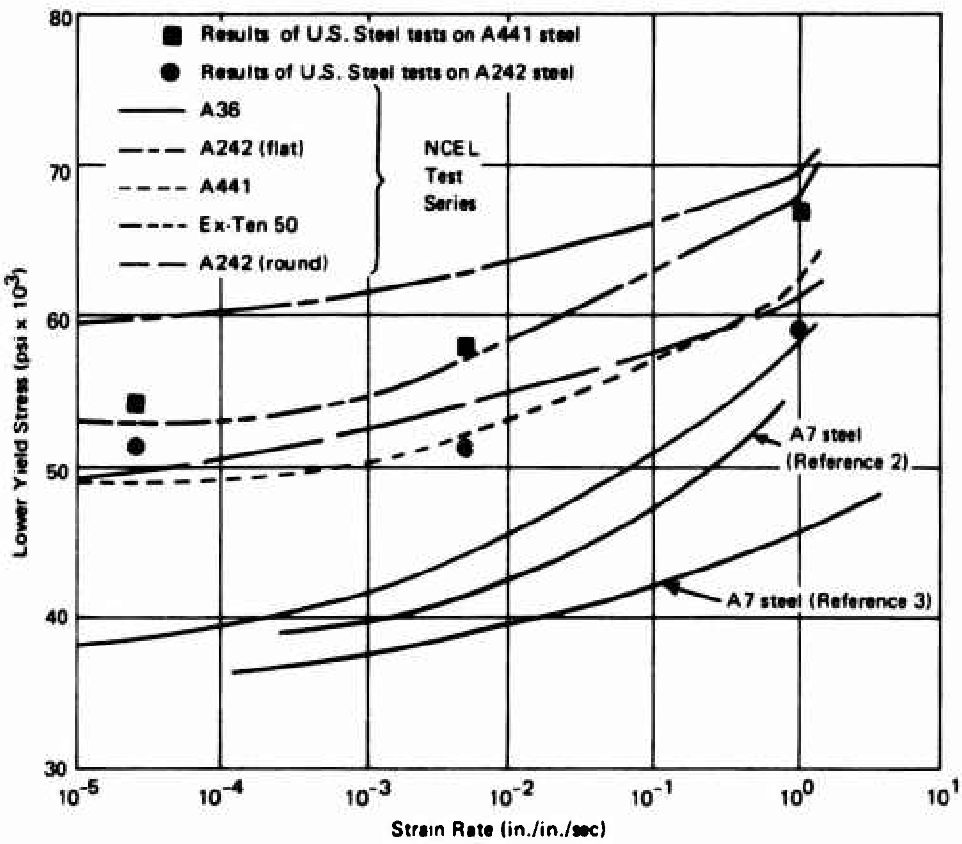

Figure 18. Lower yield stress versus strain rate for structural steels.

The A36 and Ex-Ten 50 steels showed an increase in plastic elongation with increasing strain rates up to 0.5 in./in./sec. The plastic range for A36 steel increased from a static value of 1.8% to 4.3% at 0.509 in./in./sec (Figure 6). At the maximum elastic strain rate of 1.35 in./in./sec, the plastic range decreased to a value of 2.7%. The Ex-Ten 50 static value was 2.2% and registered 4.0 and 3.1% at elastic strain rates of 0.52 and 1.41 in./in./sec, respectively (Figure 10). The other materials showed minor variations in plastic strain, but there was no significant trend.

No significant change in ductility was observed in any of the steels tested.

Strain-Aging Test Series

The results of tests conducted on strain hardened and aged material did not indicate any adverse reactions to dynamic loading. The only steel that showed a significant effect from the aging treatment was the A36 steel.

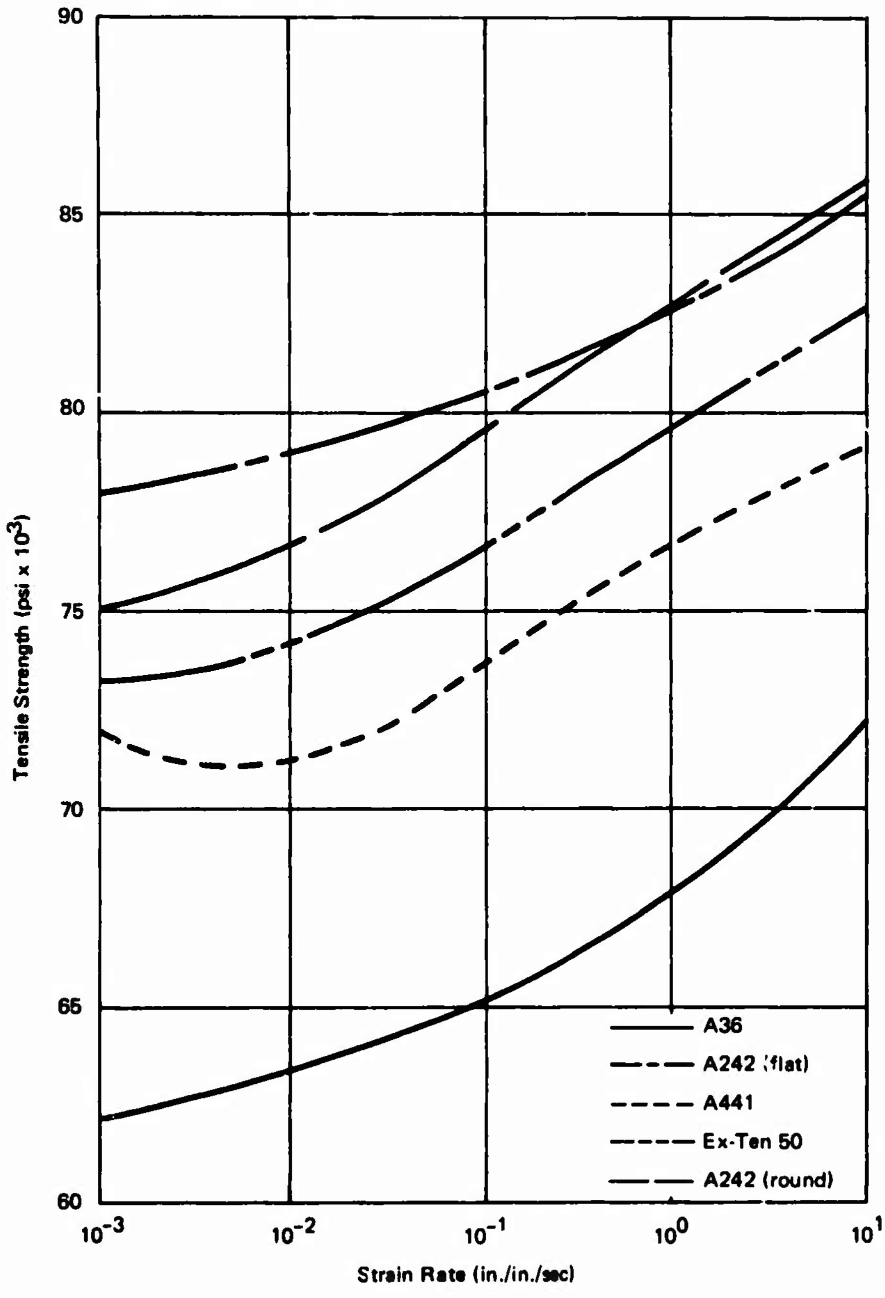

Figure 19. Tensile strength versus strain rate for structural steels.

As illustrated in Figures 15 and 16, the aging treatment not only brought back the yield point but increased the stress level of the stress–strain curve. The aging process takes a considerable length of time for this steel at room temperature. The first indication of aging appeared after a 4-hour rest period as a slight increase in stress level before uniform straining continued. After 24 hours of rest the yield point had returned, but no significant change had taken place in the remainder of the stress–strain curve. After 862 hours, no change was observed in the yield stress, but there is a reduction in elongation. When the specimens were aged at 60°C the aging process was accelerated compared to when they were aged at room temperature. The resulting slightly higher level of stress indicates that aging at room temperature was not entirely complete at 862 hours.

The dynamic tests conducted on the strain-aged A36 steel at 0.5 in./in./sec showed a significant increase in lower yield and ultimate strength over the corresponding unaged specimens tested at the same strain rate (Figure 11). In particular, the lower yield and strain-hardening portion of the stress–strain curve was raised significantly.

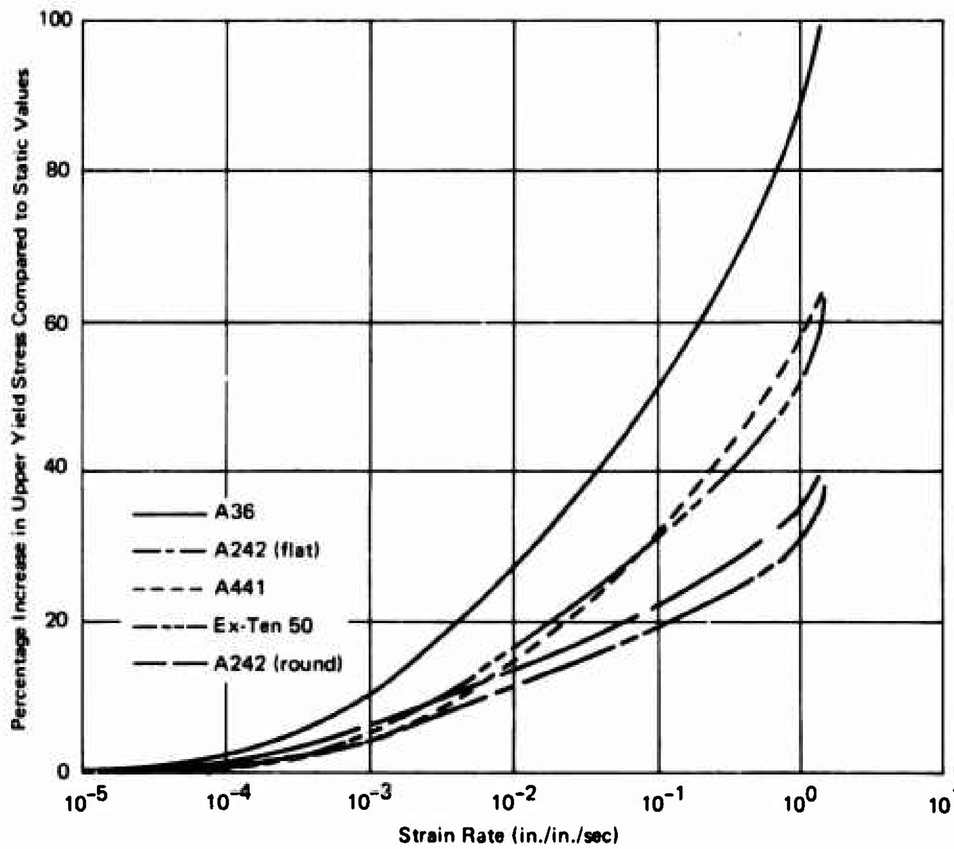

Figure 20. Percentage increase in upper yield stress compared to static values versus strain rate for structural steels.

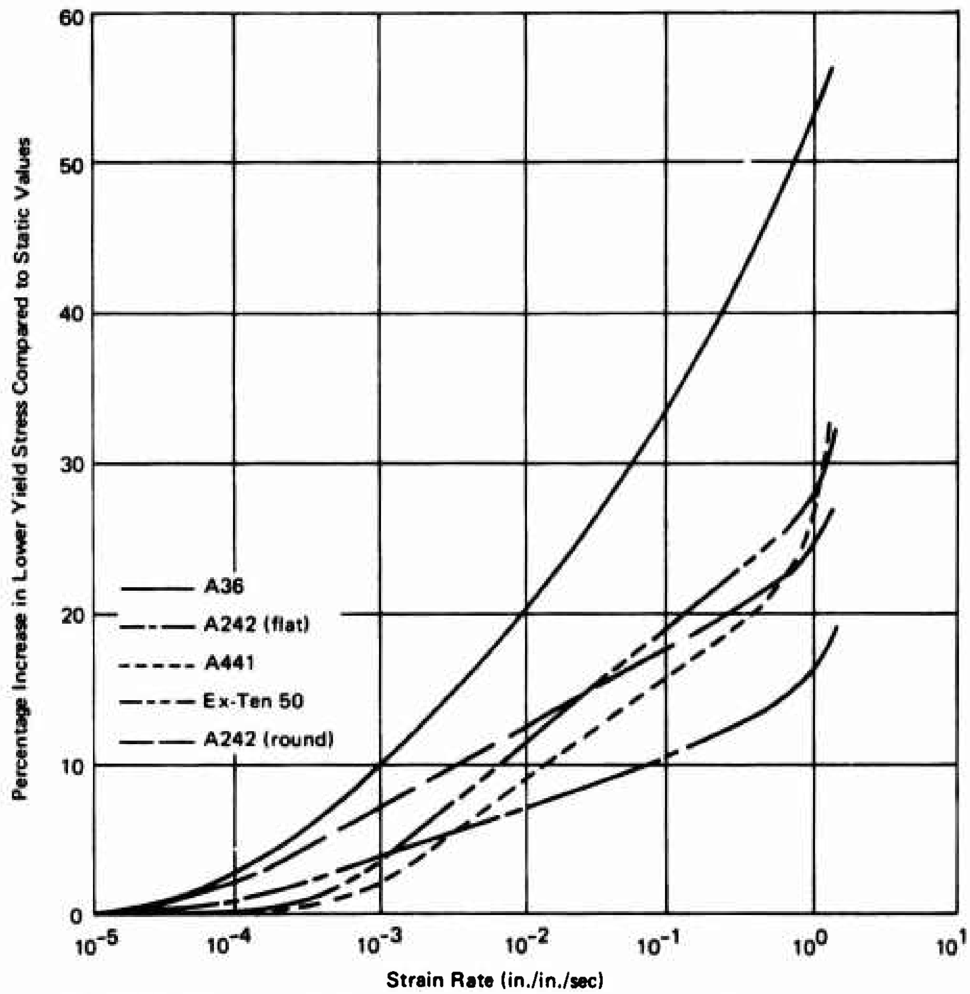

Figure 21. Percentage increase in lower yield stress compared to static values versus strain rate for structural steels.

The remaining steels showed very little change due to the aging treatment. (See Figures 12, 13, and 14.) The only signficant characteristic identifiable as a result of aging these specimens was a return of the yield point and a short plastic range. Additional aging did not alter these characteristics. It might appear that the Ex-Ten 50 steel specimens showed a slight increase in mechanical properties due to aging, but it should be noted that the initial stress–strain curves of these specimens up to 4% strain were also higher than the original static test curves.

COMPARISON WITH WORK OF OTHER INVESTIGATORS

There are few tests with which the present data can be compared. Tests were conducted by the Southern Research Institute for U. S. Steel[5] on several high-strength steels. The results of tests conducted on A242 and

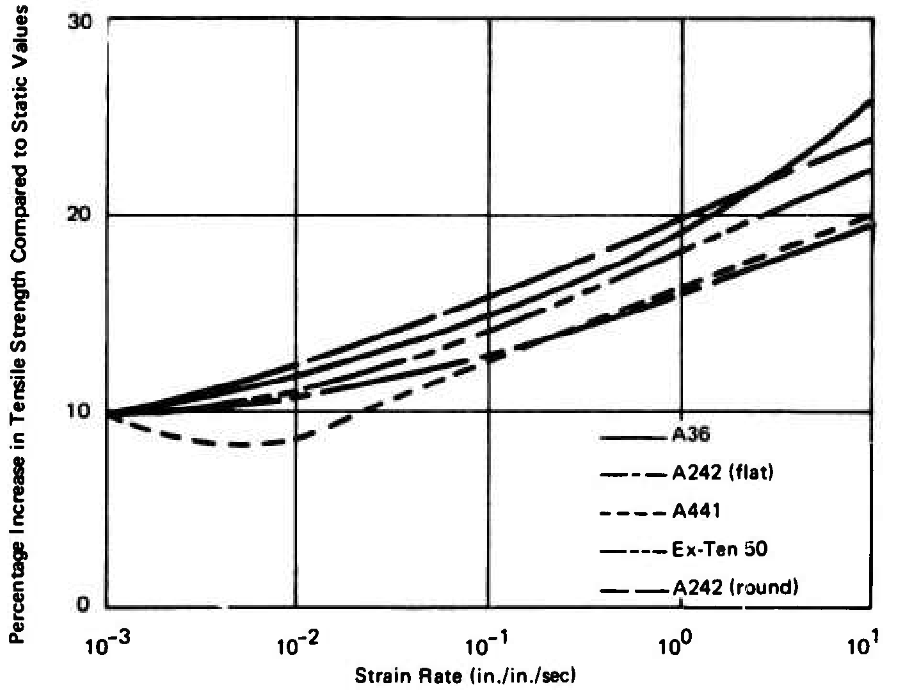

Figure 22. Percentage increase in tensile strength compared to static values versus strain rate for structural steels.

A441 steels are illustrated in Figure 18. These tests indicate a smaller response to increasing strain rates than the tests conducted at NCEL for the A242 steels and good correlation between the A441 steels. Figure 18 also shows the recommended yield stress values from the Air Force Design Manual[2] (AFDM) and the Corps of Engineers Manual[3] (CEM) for A7 steels. The curves in these manuals present the yield stress as a function of time to yield. A value of 30 x 10^6 psi was used for the modulus of elasticity to convert the curves to a strain rate function. The general shape of the AFDM curves is similar to that found for the A36 steel. The CEM curve is much more conservative. Recommended dynamic increase factors for the structural steels tested are shown in Figure 23. Values should be applied to the minimum yield stress for each class of steel.

The phenomenon associated with the aging of strained steel is generally attributed to the fact that nitrogen and carbon atoms enter the dislocations during their diffusion through the steel; this anchors the dislocations and thus strengthens the steel. When a strain-aged specimen is retested the yield point returns, and some degree of increase in yield stress may be evident. Strain aging is controlled by lowering the amount of carbon and nitrogen in solution by adding elements such as aluminum, vanadium, titanium, columbium and boron to form stable carbides and nitrides. Dieter[6] states: "While a certain amount of control over strain aging can be achieved, there is no commercial low carbon steel which is completely non-strain aging."

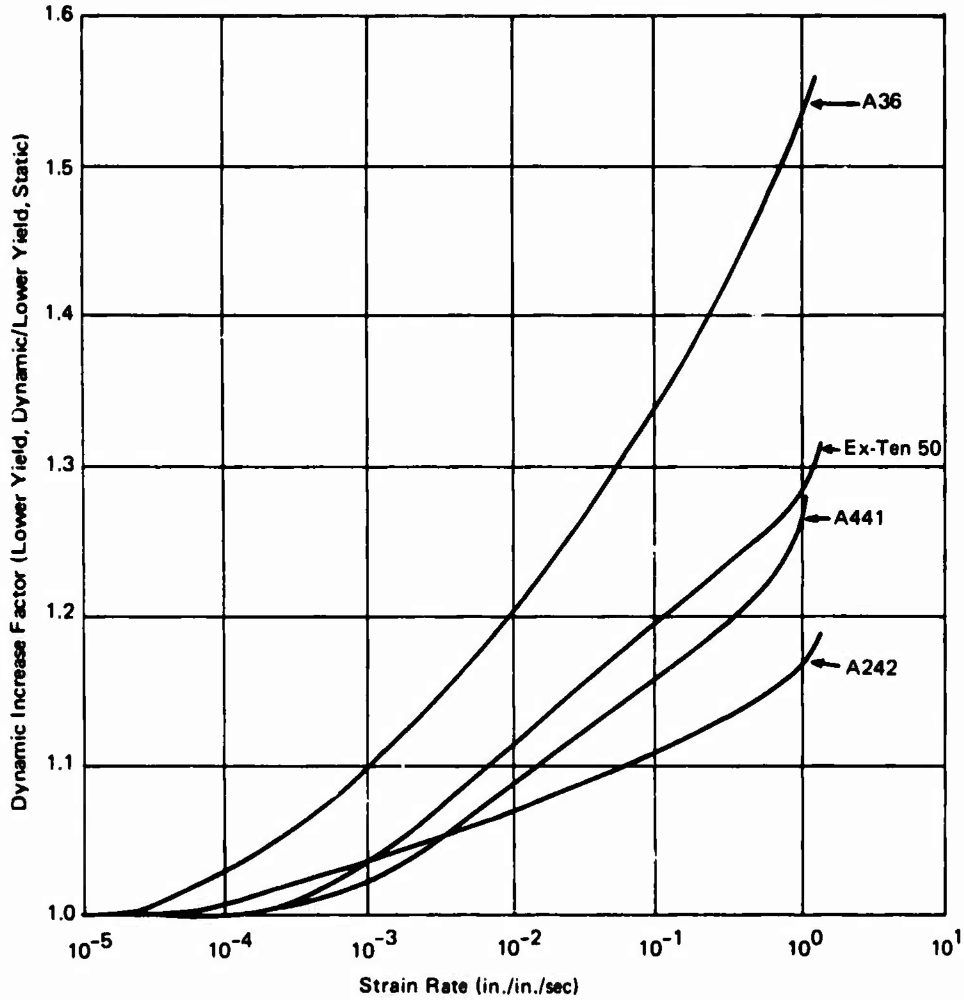

Figure 23. Recommended lower yield stress values for structural steels.

For strain aging to be of value to the designer of structures intended to resist blast loadings from multiple-warhead weapons, the aging process would have to take place in a time period of seconds or less. Extensive testing by Leslie and Rickett[7] showed that the aging of a low carbon steel could be completed in 1 minute if the aging temperature were raised to 149°C. At 67°C only a very small effect could be observed due to aging for a period of 5 minutes. For the steels tested by Leslie, the maximum percentage increase in yield stress over the stress at 4% strain during the initial loading was 18%. This increase is comparable to the 17% increase observed in the NCEL tests. It would appear that the rate and extent of strain aging is much too variable to be incorporated into the design of any structure.

Of more interest to the designer is the potential embrittlement of strain-aged materials to impact loads. It is possible for areas of structural steel members to be strained past the yield point during erection. Reference 8 shows the change in impact transition temperature that took place in a 0.19% carbon, 0.74% manganese, semi-killed steel. The transition temperature increased from $-29^{o}C$ to $-1^{o}C$ after the steel had been strained 10%. Aging the steel for 1 hour at $288^{o}C$ raised the transition temperature to $27^{o}C$. Results in the current tests at NCEL did not indicate any excessive reduction in ductility in any of the steels tested; however, it would seem appropriate to investigate this area further by conducting similar tests at low temperatures.

FINDINGS AND CONCLUSIONS

1. In all of the steels, the mechanical properties exhibited increased values as the strain rate of testing increased. Therefore, there are no adverse effects to structural steel due to dynamic loading.

2. The A36 steel was the most strain-rate sensitive of all the steels tested.

3. No adverse effects were found due to the strain aging of the steels tested; however, a reduction in elongation of 4% was observed in the A36 steel.

4. The A36 steel was the only steel tested that exhibited an increase in yield stress over the stress necessary to produce the initial 4% strain.

5. The A36 steel was the only steel tested that showed a significant increase in the values of dynamic mechanical properties when compared to unaged specimens tested at the same strain rate.

RECOMMENDATIONS

1. The effects of low temperature on the dynamic properties of strain-aged structural steels should be investigated.

2. Design recommendations are given in Figure 23 for the increase factors to be applied to the lower yield stress for each grade of structural steel.

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Naval Civil Engineering Laboratory
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by W. L. Cowell
TR-642   23 p. illus   September 1969   Unclassified

1. Structural steel   2. Dynamic tests   I. Y-F008-08-03-401   II. DASA SC318

Dynamic tension tests and static tension tests were conducted on four grades of structural steels. The steels conform to ASTM grades A36, A242, A441, and A572. Stress–strain curves are presented for each steel at various strain rates, ranging from static to about 1.5 in./in./sec. While all steels showed an increase in yield stress with increasing strain rates, the A36 steel showed the greatest increase. Design recommendations are given for structural steels subjected to high strain rates.

Additional specimens were strain aged, and stress–strain curves were obtained for both dynamic and static tests. Of the strain-aged steels, only the A36 steel showed a significant increase in strength over the non-strain-aged steels, when loaded dynamically. No adverse effects of strain aging were noted on any of the steels.

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